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Cognitive Nonlinear Radar

by Anthony Martone, David McNamara, Gregory Mazzaro, and Abigail Hedden

ARL-MR-0837 **January 2013**

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ARL-MR-0837 **January 2013**

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
January 2013

2. REPORT TYPE
Progress

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Cognitive Nonlinear Radar

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Anthony Martone, David McNamara, Gregory Mazzaro, and Abigail Hedden

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: RDRL-SER-U
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-MR-0837

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this report, a unique cognitive nonlinear radar (CNR) is introduced. Research and development efforts for the CNR are currently funded by the U.S. Army Research Laboratory (ARL). The CNR adapts to (1) an increasingly cluttered electromagnetic (EM) environment, a growing problem for ground-based and airborne radar systems; (2) multiple targets; and (3) other radar, communication, and electronic systems that must operate without interfering with each other. The CNR uses a narrowband, nonlinear radar target detection methodology. This methodology has the advantage, as compared with other nonlinear radar systems that do not implement a cognitive scheme, to adapt to the radio frequency (RF) environment by intelligently selecting waveform parameters using adaptive algorithms. The adaptive algorithms optimize the waveform parameters based on (1) the EM interference, (2) target likelihood, and (3) permissible transmit frequencies as specified by regulations and allowable by other systems operations within the environment.

15. SUBJECT TERMS
cognitive radar, adaptive sensing, spectrum sensing, multi-objective optimization, genetic algorithms, machine learning

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Anthony Martone
Unclassified	Unclassified	Unclassified	UU	18	19b. TELEPHONE NUMBER (*Include area code*) (301) 394-2531

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

An increasingly cluttered electromagnetic (EM) environment is a growing problem for ground-based and airborne radar systems. This problem is becoming critical as the available frequency spectrum shrinks due to growing wireless communication device usage and spectrum management regulations. This problem is further exacerbated by the growing number of targets that the radar must detect. More capable radar systems are needed that can adapt to multiple targets while utilizing unoccupied frequency bands. Finally, radar, communication, and other electronic systems must be capable of operating without interfering with each other.

A possible solution to this problem is cognitive nonlinear radar (CNR). The CNR adapts to (1) an increasingly cluttered EM environment, a growing problem for ground-based and airborne radar systems; (2) multiple targets of interest; and (3) other radar, communication, and electronic systems that must operate without interfering with each other. The CNR uses a nonlinear radar target detection methodology. This methodology has the advantage, as compared with other nonlinear radar systems that do not implement a cognitive scheme, to adapt to the radio frequency (RF) environment by intelligently selecting waveform parameters using adaptive algorithms. The adaptive algorithms optimize the waveform parameters based on (1) the EM interference, (2) target likelihood, and (3) permissible transmit frequencies as specified by regulations and allowable by other systems operations within the environment.

The CNR is an extension of nonlinear radar. Nonlinear radar produces frequencies in a nonlinear target (e.g., electronics or metal object) that are different from those transmitted by the radar, thereby separating natural clutter from the nonlinear target response (*1, 2*). This separation is made possible by the nonlinear properties inherent to the target. Nonlinear radar systems have an early history dating back to World War II, where German V-2 missiles were fitted with nonlinear tags for tracking experiments (*3*). Other early works include nonlinear radar for automobile accident avoidance (*4, 5*) and junction range finding (*6, 7*). The junction range finder is an "apparatus for locating an electrically nonlinear object and determining the distance to object (*6*)." Nonlinear radar has also been used in military operations to detect concealed weapons, electronics, and other manmade objects (*8–16*) and electronic device detection for Federal Communications Commission (FCC) Part-15 compliance (*17*). In more recent applications, nonlinear radar has been used for insect tracking, where insects are fitted with nonlinear tags and tracked to study insect movements and foraging (*18–20*).

The cognitive processing of the CNR is based on cognitive radar. A cognitive radar learns from the environment and intelligently modifies the transmit waveform. Cognitive radar constitutes a system capable of optimizing performance using (*21*) (1) intelligent signal processing that learns from the environment; (2) receiver-to-transmitter feedback; and (3) preservation of information (i.e., memory). Cognitive radar builds from many research disciplines including adaptive radar

(*22–24*), knowledge-based processing (*25*, *26*), waveform optimization and adaptation (*27*, *28*), machine learning and pattern precognitive (*29*, *30*), and spectrum sensing (*31*).

In this report, the processing of a CNR is introduced. The processing uses a frequency selective approach to exploit the nonlinear properties of the target of interest (TOI). The three main elements of the cognitive processing include spectrum sensing, target detection and classification, and an optimizer. Spectrum sensing is used to identify frequency locations of RF interference to avoid transmitting and receiving at those interference locations. Spectrum sensing is also used to identify patterns of transmitted waveforms commonly used by communication and RF systems. Target detection and classification methods exploit a priori target signatures in a database. The optimizer intelligently selects a set of waveform parameters based on target likelihood and RF interference. As is discussed in section 2, this processing is iterative and with the goal of indicating the presence or absence of a nonlinear target with high confidence.

2. Cognitive Nonlinear Radar Processing

The CNR operational method is illustrated in figure 1. The system uses a frequency selective approach to exploit the nonlinear properties of the TOI. A database is used to identify a frequency band and sub-bands of interest based on a priori target information, which indicates the areas of spectrum inside of which a target is likely to respond to RF (figure 1a). The database is also used to access known RF system waveform types, thereby allowing the CNR to avoid (1) interfering with other RF systems and (2) being interfered with by other RF systems. The RF environment is passively scanned for noise, RF interference, and known RF system waveforms (figure 1b). Radar waveform parameters are then selected based on RF interference and noise power levels (from the passive scan) at potential transmitter and receiver frequencies; both transmitter and receiver frequencies are considered since the nonlinear target produces frequencies different from those transmitted by the radar. Radar waveform parameters are also selected based on a priori target information (provided by a database). Selection of the radar waveform parameters is made by adaptive algorithms designed to solve a multi-objective optimization problem. A radar probe signal then illuminates the environment and the radar return is measured (figure 1c). The measured radar return is then processed for a nonlinear response indicating the presence or absences of a TOI. New radar waveform parameters are selected for the next iteration based on (1) a passive measure of RF interference and noise, (2) a priori target and database information, and (3) the likelihood of the TOI based on the previous iteration. Therefore, for a given iteration, the frequency of the new radar waveform can change to a new sub-band (figure 1d) to verify the TOI.

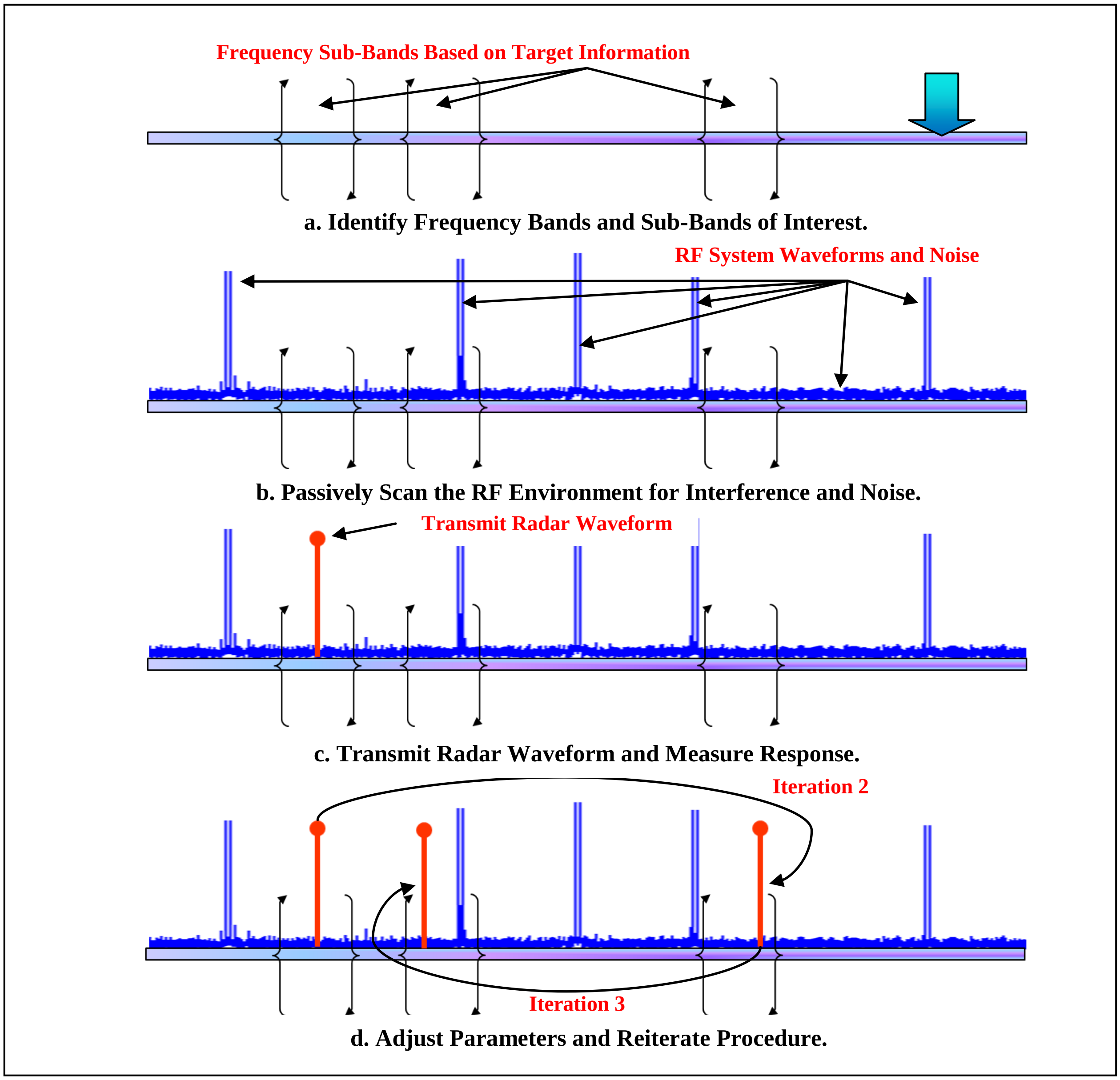

Figure 1. CNR operational method.

The processing framework of the CNR is shown in figure 2. The key contributions to the proposed cognitive radar system are highlighted in the red, dashed box labeled "cognitive processing." Multiple receivers are needed and are grouped into two categories: (1) an array passive spectrum receivers and (2) the radar receiver. The passive spectrum receivers sense the RF environment to detect EM interference. Multiple passive receivers are implemented to measure multiple bands/channels of interest simultaneously. Multiple receivers have the advantage, as compared with a single passive receiver, of reducing the time needed to measure multiple frequency bands of interest. Spectrum sensing techniques process the passive measurements for noise, interference, and RF signals operating in the RF environment so that the

radar transmitter and receiver operate in bands outside these preexisting signals. After an appropriate waveform has been chosen for target detection, the radar receiver measures the RF environment in response to the transmit waveform. Potential target information, or features, are extracted from the radar receive signal. The signal-to-noise ratio (SNR) is estimated using the features (from the radar receiver processing chain) and the interference and noise (from the passive receiver processing chain). Target detection and classification algorithms then process the SNR signal along with a priori target information, such as the amplitude of the harmonics generated by the target, to detect and classify targets of interest. The parameters for the transmitted waveform (i.e., amplitude, frequency, phase, modulation, etc.) are optimized based on target detection likelihood, noise and interference power levels, and permissible transmit frequencies (as specified by the database). The waveform is then selected and transmitted. This process reiterates until the presence or absence of a nonlinear target is determined with high confidence.

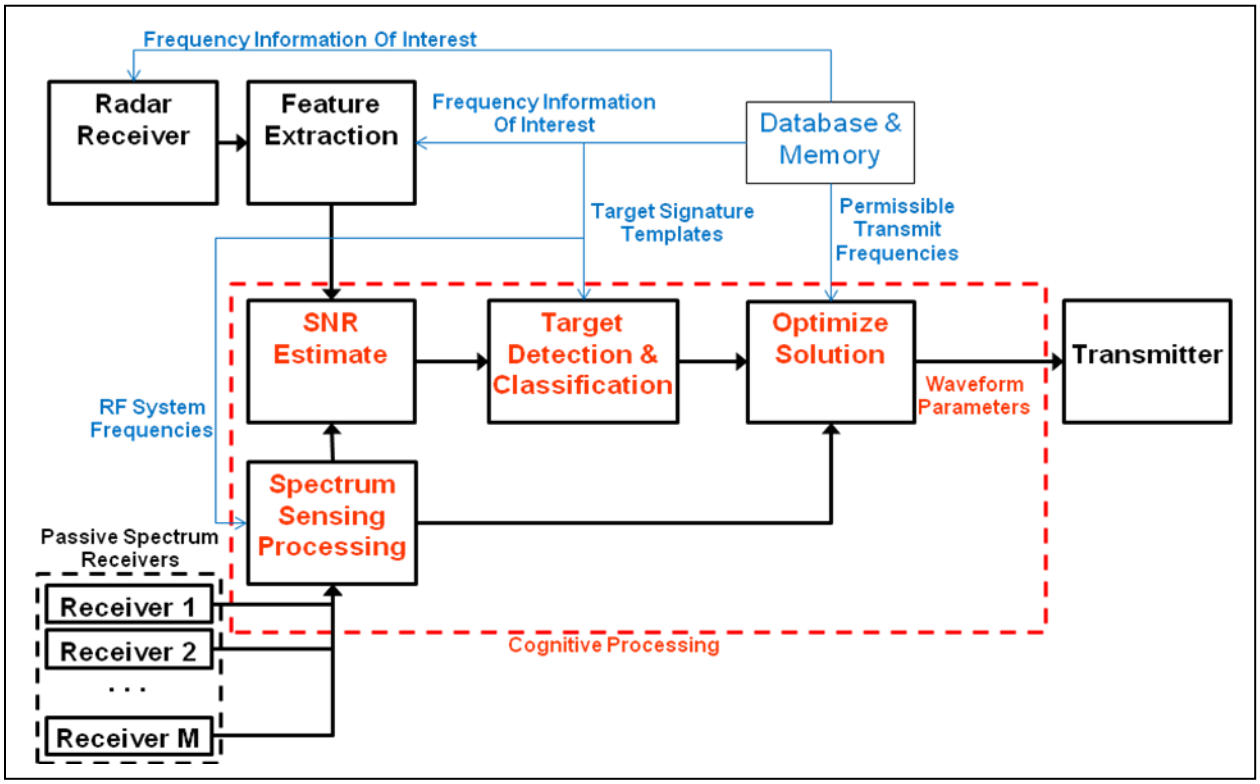

Figure 2. CNR processing.

The spectrum sensing processing of figure 2 is used to estimate the power spectrum from the finite duration data stream provided by the passive spectrum receivers. The passive spectrum receivers (with analog-to-digital conversion) provide digitized data stream of information. Figure 3 illustrates the spectrum sensing processing. A window function is used to reduce spectral leakage, or sidelobes, due to a finite observation window and the estimate of the power spectrum is efficiently computed using the fast Fourier transform (FFT). The power spectrum is

then used in conjunction with features extracted from the radar receiver information to estimate SNR for target detection and classification. Finally, a signal detection technique is used to detect potential communication and other RF signals operating in the RF environment. The signal detection technique accesses the database for known RF system waveform types. The optimized solution processing block (as shown in figure 2) must consider potential communication and other RF signals to avoid interfering with RF systems. The optimized solution also processes the estimated power spectrum to identify the frequencies of interference and noise at low power levels; this information is used (in part) to select the transmit frequency for the next iteration.

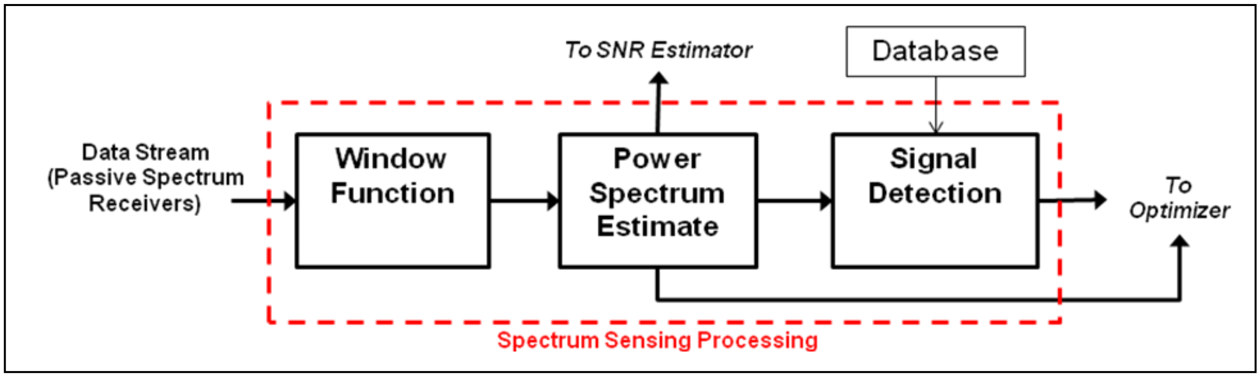

Figure 3. Spectrum sensing processing block diagram.

The target detection and classification technique is illustrated in figure 4. The inputs to the detector are SNR estimate of harmonic and/or intermodulation distortion products. A target detector determines the likelihood of detection for each feature. Several target detection methodologies exist and include match filter, Bayesian decision theory, Generalized Likelihood Ratio Test (GLRT), and constant false alarm rate (CFAR) processing (*31*). Once the likelihood of the features is accessed, they are classified to identify a target type. Common classification methodologies include Bayesian discriminate functions, nearest neighbor classifiers, support vector machines (SVM), neural networks, tree-based algorithms, and unsupervised learning algorithms (*29*). Finally, costs are assigned to frequencies based on the classification label. For example, consider the situation where "Target 1" is identified by the classifier with medium likelihood. The objective of the proposed cognitive radar system is to increase the likelihood of Target 1 from medium to high. One procedure to increase the likelihood of Target 1 would be to transmit frequencies in bands where Target 1 is known to respond. Low costs are therefore assigned to Target 1 transmit frequencies and high costs are assigned to the other target transmit frequencies. The cost information is provided to the optimizer.

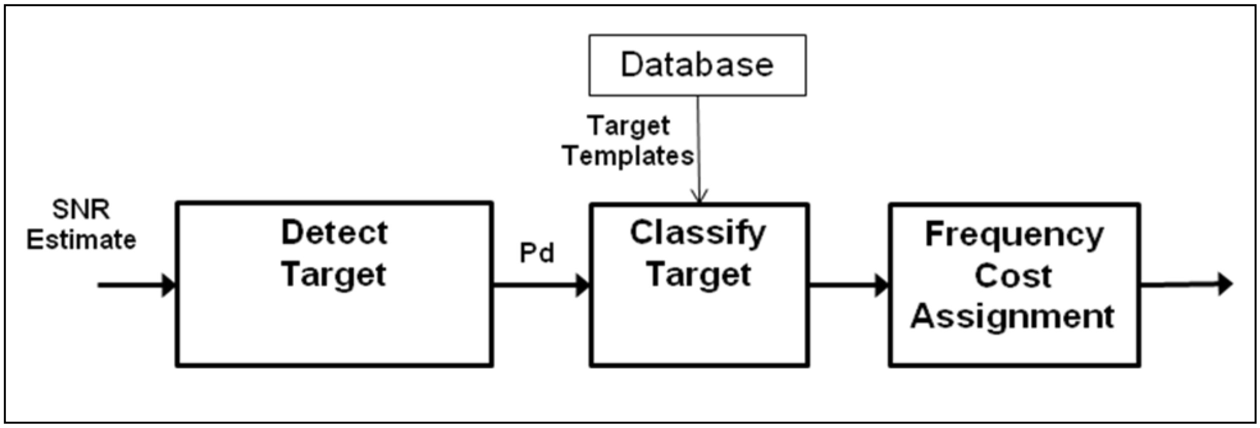

Figure 4. Target detection and classification block diagram.

After target detection and classification, the optimizer is used to determine parameters of a new transmit frequency and other waveform parameters based on the frequency cost information, permissible transmit frequencies provided by the database, and available transmit frequencies provided by the spectrum sensing procedure. The optimizer must minimize multiple objective functions that are non-commensurable. The formulation of the multi-objective optimization problem is as follows (*30*): for a given decision variable vector $\vec{x} = \{\vec{x}_1, \vec{x}_2, ...\vec{x}_M\}$ in the solution space *X*, the optimizer must find a vector $\vec{x}*$ that minimizes a set of *k* objective functions $z(\vec{x}*) = \{z_1(\vec{x}*), ...z_k(\vec{x}*)\}$. Objective functions, as related to radar systems, include SNR, system power consumption, frequency costs (as provided by the target detection and classification scheme), occupied bandwidth, and computational complexity. The decision variables in related to radar systems, include frequency, signal power, bandwidth, modulation type, and pulse repetition interval (PRI).

Given multiple objective functions, the optimization problem is formulated as a multi-objective optimization problem, a well-studied topic. Solutions to multi-objective optimization problems consist of finding the Pareto optimal set (*32*), a surface of non-dominated solutions. Non-dominated solutions are determined based on their superiority to all other solutions in the solution space. The set of non-dominated solutions are optimal because the solutions are neither superior nor inferior to one another. Genetic algorithms can then be used to solve the multi-objective optimization problem. Note that genetic algorithms should only be implemented for a large solution space. Genetic algorithms search difference regions of the solution space in parallel allowing for complex solutions with non-convex, discontinuous, and multimodal solution spaces (*30*). The search method used by genetic algorithms is randomized and therefore permits a rapid global solution and avoids losing potential non-optimal solutions (*33, 34*). Genetic algorithms are advantageous compared with other machine learning solutions since they do not require training data or statistical models of the target and/or environment.

The basic procedure of a genetic algorithm is shown in figure 5 (*29*). A set, or population, of *N* solutions is randomly generated. The solutions in the population are binary strings of

chromosomes. The fittest chromosomes in the population are identified using a fitness measure, which is dependent on the objective functions. Crossover is then used to mix (or mate) two chromosomes by splitting each chromosome at a random point and then attaching the end of one chromosome to the end of the other chromosome. Mutation is then used to switch a bit in the chromosome at a random location. A new population, i.e., the next generation, is formed after the crossover and mutation process. The chromosomes in the new population are evaluated for fitness and non-dominated solutions are identified (if any exist). A stopping criterion is finally evaluated to determine if the new population meets the requirements of the optimization process.

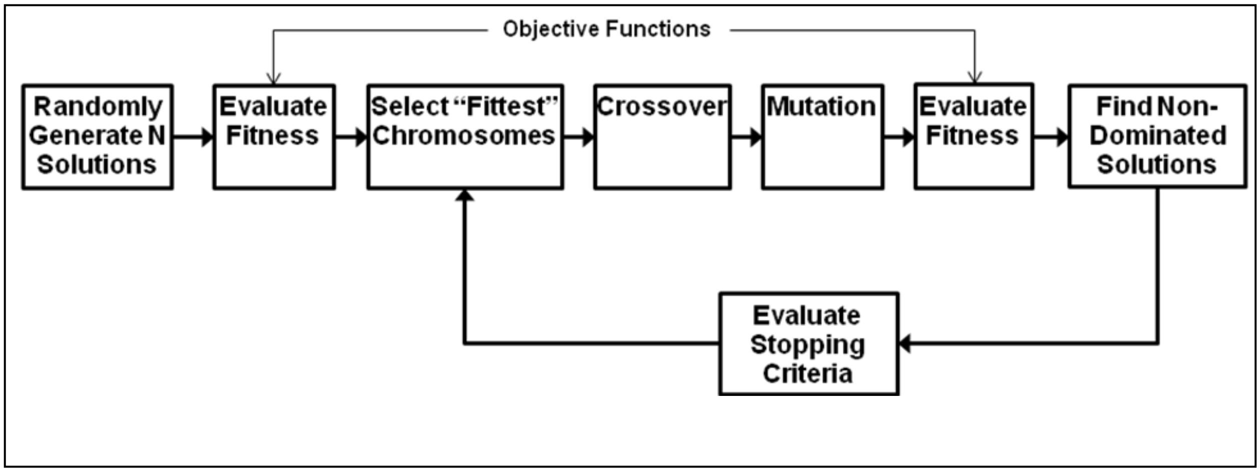

Figure 5. Genetic algorithm block diagram.

3. Conclusion

In summary, the processing of a CNR was introduced in this report. The processing uses a frequency selective approach to exploit the nonlinear properties of the TOI. The three main elements of the cognitive processing include spectrum sensing, target detection and classification, and optimization. Spectrum sensing is used to (1) identify frequency locations of RF interference to avoid transmitting and receiving at those interference locations; and (2) identify patterns of transmitted waveforms commonly used by communication and RF systems. Target detection and classification methods exploit nonlinear a priori target signatures. The optimizer intelligently selects a set of waveform parameters based on target likelihood and RF interference.

In future work, the spectrum sensing, target detection and classification, and optimization algorithms will be developed. Once developed, the algorithms will enable cognitive decision making for the CNR. It is envisioned that this framework can be expanded into a proof-of-concept test-bed to develop and analyze current and future algorithms.

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List of Symbols, Abbreviations, and Acronyms

CFAR	constant false alarm rate
CNR	cognitive nonlinear radar
EM	electromagnetic
FCC	Federal Communications Comission
FFY	fast Fourier transform
GLRT	Generalized Likelihood Ratio Test
PRI	pulse repetition interval
RF	radio frequency
SNR	signal to noise ratio
SVM	support vector machines
TOI	target of interest

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